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Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

DESIGN AND PERFORMANCE OF A MICROPROCESSOR-BASED AUTOMATED CONTINUOUS MONITOR WITH α-SPECTROSCOPY CAPABILITIES FOR THE DETERMINATION OF RADON AND THORON AND THEIR SHORT-LIVED DECAY PRODUCTS

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ELLIOT LAKE LABORATORY

SEPTEMBER 1983

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MICROMEDIA

DEC 22 1983

28 pp

MINERALS RESEARCH PROGRAM
MINING RESEARCH LABORATORIES
DIVISION REPORT MRP/MRL 83- 78 (TR)

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by

J. Bigu*, R. Kaldenback+ and M. Grenier**

ABSTRACT

A microprocessor controlled instrument has been developed for continuous, unattended, long-term monitoring of ambient concentration of radon and thoron gas and their short-lived decay products, i.e., daughters. The instrument basically consists of two independent although interconnected systems. The primary system is designed to determine radon and thoron daughters and consists of a sampling head housing a filter facing a ruggedized Si-barrier detector. The secondary system has been designed to measure radon and thoron gas concentrations. It consists of an electrostatic precipitator (a cylindrical tank of 3 L volume) operated from a 1500 VDC voltage supply. A custom designed Si-barrier wafer detector is located at the centre of the precipitator and is galvanically connected to ground potential. The primary and secondary detectors are fed through charge-sensitive preamplifiers and main amplifiers to identical spectroscopy grade multichannel analyzers. The instrument is of the active kind, i.e., uses a sampling pump to collect and carry the radioactive gases and their daughter products. The pump operates at a nominal flow rate of 1 L/min. The instrument is based on time-integrating principles. The instrument has been tested extensively under a variety of radioactive environmental conditions, and should prove quite useful in environmental monitoring for health physics, occupational and engineering purposes.

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CONCEPTION ET PERFORMANCE D'UN MONITEUR AUTOMATIQUE CONTINUEL PAR MICROPROCESSEUR A OPTIONS DE SPECTROSCOPIE α POUR L'ÉVALUATION DES CONCENTRATIONS DU RADON, DU THORON ET DE LEURS DESCENDANTS À COURTE DURÉE

J. Bigu*, R. Kaldenback** et M. Grenier†

RÉSUMÉ

On a mis au point un instrument commandé par microprocesseur pour l'écoute continue à long terme et sans opérateur de concentrations ambiante des gaz radon et thoron et de leurs produits de filiation de courte durée, c.-à-d. leurs descendants. L'instrument se compose essentiellement de deux systèmes indépendants, cependant reliés. Le système primaire est conçu pour l'évaluation des concentrations des descendants du radon et du thoron, et comprend une tête de prélèvement logeant un filtre placé devant un détecteur robuste à barrière de Si. Le système secondaire a été conçu pour la mesure des concentrations de radon et de thoron. Il comprend un précipitateur électrostatique (réservoir cylindrique de 3 L) maintenu par une alimentation de 1500 V, courant direct. Une pastille détectrice à barrière de Si, faite sur mesure, est placée au centre du précipitateur et mise à la masse par un lien de type galvanique. Les détecteurs primaire et secondaire sont reliés à des préamplificateurs sensibles aux charges éléctrique et à des amplificateurs principaux puis à des analyseurs spectroscopiques multivoies identiques. L'instrument est du type actif, c.-à-d. qu'il utilise une pompe de prélèvement pour receuillir et transporter les gaz radioactifs et leurs decendants. La pompe a un débit nominal de 1 L/min. L'instrument est basé sur les principes d'intégration de temps. Il a été soumis à des essais pousés sous une variété de milieux radioactifs et devrait se révéler très utile pour évaluer le millieu vis-à-vis la radioprotection et des fins occupationnelles et d'ingénérie.

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INTRODUCTION

Radiation environments pose potential hazards to human health, hence, the need for adequate monitoring of radiation levels. Radiation monitoring is also important for engineering purposes such as the maintenance of reliable air quality control in working areas.

Monitoring of radiation levels is accomplished essentially by two different methods: a 'discrete' one normally known as grab-sampling, and a continuous method, generally referred to as continuous monitoring. Grab-sampling is conceptually simple and relatively inexpensive from the instrumentation point of view, but usually requires a great deal of manual operation which severely limits its capabilities. Continuous monitoring is considerably more complex instrumentally and analytically, but the automated nature of the sampling and the analysis processes makes it clearly preferable when large amounts of data are required, as is the case in a variety of engineering, industrial and research applications and for health physics purposes.

Monitoring of radon decay products, i.e., radon daughters, in uranium mines for dose exposure purposes is mandatory in Canada and in other countries. However, until recently, the contribution from thoron daughters to total dose exposure was usually ignored because their presence in uranium mines was assumed to be negligible. Recent data, however, indicate thoron concentrations in some locations to be much higher than originally thought or anticipated (1). Consequently, monitoring of thoron daughters in addition to radon daughters is both important and useful. Furthermore, the presence of thoron daughters interferes with the accuracy in the determination of radon daughter levels and, therefore, introduces errors in the calculation of dose exposure to occupational workers.

The need for reliable instrumentation for monitoring radon daughters

and thoron daughters is, therefore, felt in view of the recent interest and emphasis placed on the potential health hazards associated with the inhalation of thoron daughters in uranium mines, mills and other radiation sites. Concurrent monitoring of radon daughters and thoron daughters is also useful as their relationship provides a good indicator of ventilation performance and, in addition, sheds light on other problems of considerable practical and theoretical importance.

In spite of the recent proliferation of radiation instrumentation for estimating radon and thoron decay products, there is room for an automated area monitoring instrument with memory storage capabilities suitable for unattended monitoring for extended periods of time. Such an instrument could be used extensively in underground environments for air quality monitoring purposes. An instrument of this kind, operating on time-integrating principles, has been designed and built by EDA Instruments (Toronto) under CANMET (Energy, Mines and Resources Canada) Contract DSS-23SQ23440-9-9017. The instrument has been thoroughly tested at the Elliot Lake Laboratory (CANMET). Some of the data obtained are presented in this paper. The instrument is commercially known as the RGA-400.

DESCRIPTION OF THE INSTRUMENT

The RGA-400 Radon/Thoron Gas Analyzer is a sophisticated outgrowth of another instrument, the WLM-300, initially designed for continuous environmental monitoring of radon (thoron) Working Levels in residential and industrial areas, in general, and in the uranium mining and milling industries, in particular. As with the WLM-300, the RGA-400 operates on time-integrating principles. Both instruments have been extensively tested in underground uranium mines in the Elliot Lake area and at the Elliot Lake Laboratory (2,3,4).

The RGA-400 is a microprocessor controlled instrument which has been developed for continuous, unattended, long-term monitoring of ambient concentration of radon and thoron gas and their respective short-lived decay products (daughters), as well as for real-time and average radon and thoron Working Level determinations.

The instrument basically consists of two independent although interconnected detection systems. The primary system is designed to determine radon and thoron daughters. It consists of a sampling head housing a Millipore 0.8 μm filter, on a special mount, facing a ruggedized Si-barrier detector. Air is drawn through the filter by means of a servo-controlled pump operating at a nominal flow rate of 1 L/min. The daughter products deposited in the filter are measured by the detector and its associated electronic circuitry. After passing through the filter, the daughter-free air passes through a second detection system, or secondary system.

The secondary system has been designed to measure radon and thoron gas concentrations. It is basically an electrostatic precipitator consisting of a hermetically sealed cylindrical tank with a volume of 3 L. The tank is operated from a 1500 VDC voltage supply and is mounted in a coaxial shield to minimize pick-up from stray electric fields and other sources of electrostatic noise. A custom designed surface-barrier wafer detector is located at the centre of the gas exhaust end of the tank. The entrance window of the detector is galvanically connected to ground potential. The tank is at + 1500 VDC relative to the detector. Gas enters the tank through four inlet ports on the end of the tank opposite the detector and is exhausted through four exhaust ports situated on the opposite end of the tank, i.e., where the detector is located. The inlet and exhaust ports are symmetrically located and equally spaced in order to provide uniform flow of gas through the tank. The sampling pump, referred to above, is located immediately after the tank exhaust. Because

the efficiency of the secondary system depends on environmental conditions a combined temperature/relative humidity probe before the tank gives information regarding these two variables.

The primary and secondary surface barrier detectors are fed to identical spectroscopy grade multichannel analyzers (MCA). The signal from each detector is fed to a charge-sensitive preamplifier and to a main amplifier. The output of the latter is fed to a 256 channel MCA.

The instrument (RGA-400) is fully programmable. Thus, the sampling intervals, sample duration, and other variables can be chosen arbitrarily. The instrument enables up to approximately 480 samples to be collected and stored in the memory. This corresponds to about 10 days of continuous data gathering with a sample duration of 30 min and 0 min interval between successive samples.

Data are displayed on command on a 64 character alpha-numeric liquid crystal display. Apart from radiation data (e.g., radon and thoron and their daughters count rates, and corresponding WL) other important data are also available including pre-filtered air temperature and relative humidity, pump flow rate, filter clogging and internal back-up battery status and date (month, day, hour and minute). Data are retrieved by means of an external printer model DCU-400 and/or a digital cassette recorder model DCU-200. The spectra corresponding to the last sample from the primary and secondary detectors can also be easily retrieved on command.

The RGA-400 comprises two 16-key keyboards. Each keyboard is layed out in a 4 x 4 key matrix. The 16 keys of one keyboard are designated the function/parameter keys while the 16 keys of the other keyboard are designated the numeric value keys and display cursor control keys.

The functions and operations of the instrument are controlled by

means of a Z-80 microprocessor and two software packages written in EDA language, not commercially available, designated "EDC".

The instrument can operate from a 110 V AC power supply or from an external battery pack (24 V DC). An internal rechargeable sealed dry lead-acid battery forms part of a no-break power supply to power the instrument (up to 4 h approximately) in case of external power failure.

THEORETICAL BACKGROUND

Radon daughter and thoron daughter information is obtained in the primary detector and associated electronic circuitry, as follows. The radon daughter Working Level, WL(Rn), corresponding to a 'pure' radon daughter atmosphere can be determined by time integrating techniques, using gross α-counting and the following expression (2,3):

$$\frac{cpm(Rn)\ F}{\varepsilon\ WL(Rn)} = CF(Rn) \qquad \text{Eq 1}$$

where, in Equation 1, cpm(Rn) represents the experimental α-count rate in counts per minute. This quantity is calculated by the instrument taking the total α-count obtained during a given, fixed, sampling interval and dividing it by the time interval. The factor F(>1) is included in Equation 1 to take into account plate-out of decay products in the sampling head and absorption of α-particles in the filter. The factor ε is the detector α-counting efficiency ($\varepsilon \simeq 0.2$). CF(Rn) is a numerical conversion factor that can be calculated theoretically and/or experimentally determined (2,3,5). It can be shown that for a constant WL(Rn), cpm(Rn) and CF(Rn) are time dependent until a radioactive steady-state condition in the sampling filter is reached, i.e., when the rate of growth of decay products accumulated in the filter, under continuous sampling at a constant flow rate, equals the rate of radioactive decay (2,5).

Similarly, the thoron daughter Working Level, WL(Tn), corresponding to a 'pure' thoron daughter atmosphere can be obtained from:

$$\frac{cpm(Tn)\ F}{\varepsilon\ WL(Tn)} = CF(Tn) \qquad \text{Eq 2}$$

Notice that although the α-energies corresponding to radon daughters and thoron daughters are different the quantities F and ε can be taken as approximately equal.

For radon/thoron mixtures the situation is more complicated but it can be shown (3):

$$WL(Rn) = \frac{cpm(total)\ (F/\varepsilon)}{CF(Rn) + CF(Tn)\ WLR} \qquad \text{Eq 3}$$

where $WLR = WL(Tn)/WL(Rn)$ Eq 4

The quantity cpm(total) represents the total α-count rate. The ratio WLR can be determined by a procedure similar to the Ogden method (6,7) suitably modified by Bigu (5) for instrumentation operating on time integrating principles. It is important to notice that as the RGA-400 has α-spectroscopy capabilities, the α-count rates in the above Equations are determined by the instrument by summation of the α-count rates corresponding to each α-energy channel. Furthermore, the α-count rates can be used to determine the corresponding decay products concentration by means of analytical procedures not yet implemented in the instrument. (The reader should be aware of the fact that there are certain limitations regarding the use of Equation 3 because of α-energy overlap (RaA and ThC) and other complicating factors are discussed elsewhere.)

The radon and thoron gas concentration can be determined in the secondary detector system, i.e., electrostatic collector. The operating principle of this system is as follows. Daughter-free radon and/or thoron from filtered air in the primary detector system, decay during their transit time through the tank into their daughter products. Initially, the daughter

products (e.g., RaA) are formed in a free (unattached), positively charged, state. Because of their charge, the daughter products are deposited (plate-out) on the detector at ground potential, where they are counted.

The secondary detection system is partly based on earlier prototypes and experimental techniques developed by Wrenn et al. (8), Negro, Watnick et al. (9,10,11) and Aprilesi et al. (12). Basically, the electrostatic collector can be considered as a two-filter method similar to that of Thomas (13) and Mayya and Kotrappa (14), where the back filter has been replaced by a solid-state detector (9) on which daughter products plate-out by electrostatic collection. Because the system operates on electrostatic principles, only charged particles plate-out on the detector. This presents a problem as neutral particles formed by attachment of recently formed daughter products to aerosols, particularly water vapour, will affect the efficiency of the system. Hence, relative humidity plays an important role as established by several authors (9,10,11,15). The efficiency of the electrostatic collector has been found to be inversely proportional to relative humidity (RH).

The radioactive gas concentration, [n], can be determined by using the following expression:

$$[n] = J(K/F_f Z_s E)\ N_\alpha(T_1,T_2)\ Bq/L \qquad \text{Eq 5}$$

where, $K = 1.66 \times 10^{-2}\ \lambda_n/\varepsilon Q$, where λ_n is the radon(thoron) radioactive decay constant and Q is the sampling flow rate (1 L/min).

The symbol Z_s in Equation 5 represents a factor for counting during sampling (see Appendix A) which differs from the expression given by Thomas (13) in that the latter is developed for counting after sampling. E is an exponential function which takes into account the decay of radon(thoron) during its transit time in the tank (14). F_f is a collection efficiency function that takes into account plate-out of daughter products on the tank walls (16).

$N_\alpha(T_1,T_2)$ is the total α-count during the sampling interval T_2-T_1. This quantity can also be calculated theoretically for comparison purposes (see ref. 5). J is a function which takes into consideration the fraction of daughter products that combine or attach to aerosols, e.g., water vapour, to form neutral particles and hence, are not removed by plate-out on the detector, and counted. The function J is greater than unity.

Because of the α-spectroscopy configuration of the secondary detection system, $N_\alpha(T_1, T_2)$ is computed by summation of the corresponding α-energy channels, e.g., RaA and RaC' for radon and ThA, ThC and ThC' for thoron. Alternatively, expressions can be developed for Equation 5 to deal separately with the different α-particle emitters.

The above method is relatively easy to implement for 'pure' radon or thoron gas. However, for mixtures of radon and thoron, the situation is more complicated as no α-energy discrimination is possible between RaA and ThC.

Because of the sensitivity dependence of the electrostatic collector on RH, and perhaps some trace gases, the instrument needs to be calibrated in known radon(thoron) gas concentration atmospheres as a function of RH. After calibration under controlled conditions, α-count correction for RH can be carried out. The problem is solved in the RGA-400 by installing a relative humidity/temperature sensor in front of the electrostatic collector. The values for the gas RH and temperature are available at any time and can be displayed and printed-out on command. A RH correction factor routine will shortly be implemented in the instrument software to automatically correct α-count, and hence gas concentration, for RH.

As inferred above, the factor J in Equation 5 is related to RH. Although this factor could be calculated theoretically, there is some uncertainty as to its true value. Several authors have suggested the use of a desiccator

column to remove moisture from the sampled air. However, this solution introduces a substantial time delay in the instrument response. Furthermore, the column has to be changed quite frequently and it adds a considerable complication in the instrument design which makes it unsuitable for practical application, particularly unattended field work.

An important consideration regarding the behaviour of radiation time-integrating devices is that corresponding to their inherent 'inertia' to react to changing radiation conditions. The promptness with which a time-integrating instrument can react to a sudden radiation level change depends upon the sampling time (programmable in the RGA-400 from 1 min to several days) and the half-lives of the radioisotopes of interest. It can be shown that if an instrument of the time-integrating kind is subjected to a step radiation level change, it will take about 4 h, for radon daughters, and well above 12 h, for thoron daughters, to reach its final value. For periodic, very rapid, radiation level fluctuations, the instrument cannot respond fast enough and tends to smooth out these changes giving a quasi steady-state average value. Some of this behaviour will be illustrated below. This problem has been dealt with in detail by Bigu, and Bigu et al. (2 to 5).

EXPERIMENTAL PROCEDURE

The RGA-400 has been tested extensively in a large radon/thoron test facility ($\sim$26 m^3) at the Elliot Lake Laboratory (CANMET, E.M.R.) and in the field. Some data are given below.

The instrument was exposed to known concentrations of radon, or thoron, or a mixture of both. The response of the instrument under a variety of environmental conditions including RH and aerosol concentration, N, has been investigated.

Results have been compared with data obtained by concurrent measurements with other radiation instrumentation including scintillation cells and associated electronic circuitry, α-spectroscopy with a Diffused-Junction (DJ) detector, continuous β-monitoring, commercial passive radon (thoron) monitors and personal dosimeters, used as environmental monitors, of the active type, and grab-sampling using different methods. Only some of the data so far obtained are reproduced here.

Tests included the behaviour of the instrument under steady-state radiation conditions and under rapidly fluctuating conditions, including stepwise radiation fluctuations.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the α-count (RaA, RaC' and total) measured in the electrostatic collector as a function of the RH of air/radon entering the primary detection system. This test was carried out as follows. A plastic cup was designed and coupled snugly to the sampling head of the primary detection system. The cup was carefully sealed around the perimeter in contact with the sampling head to eliminate leaks. Three holes, two in the radial direction and one along the axis, were made in the cup, the first two to locate a temperature probe and a RH (dew point) probe, and the third one to admit gas into the cup. Radon gas was drawn by the RGA-400 pump from a Ra-226 source of the flow-through type (Pylon model Rn-1025 with a Ra-226 activity of ∿30 pCi) through a 50 cm column desiccator into the primary and secondary detection systems. Radon gas samples at the exhaust port of the instrument were taken periodically to determine the radon gas concentration (3328 pCi/L) going through the electrostatic collector. The instrument, source and associated instrumentation were located in a room for the purpose, and the RH in the room was controlled by means of a humidifier, dehumidifier and the column desiccator.

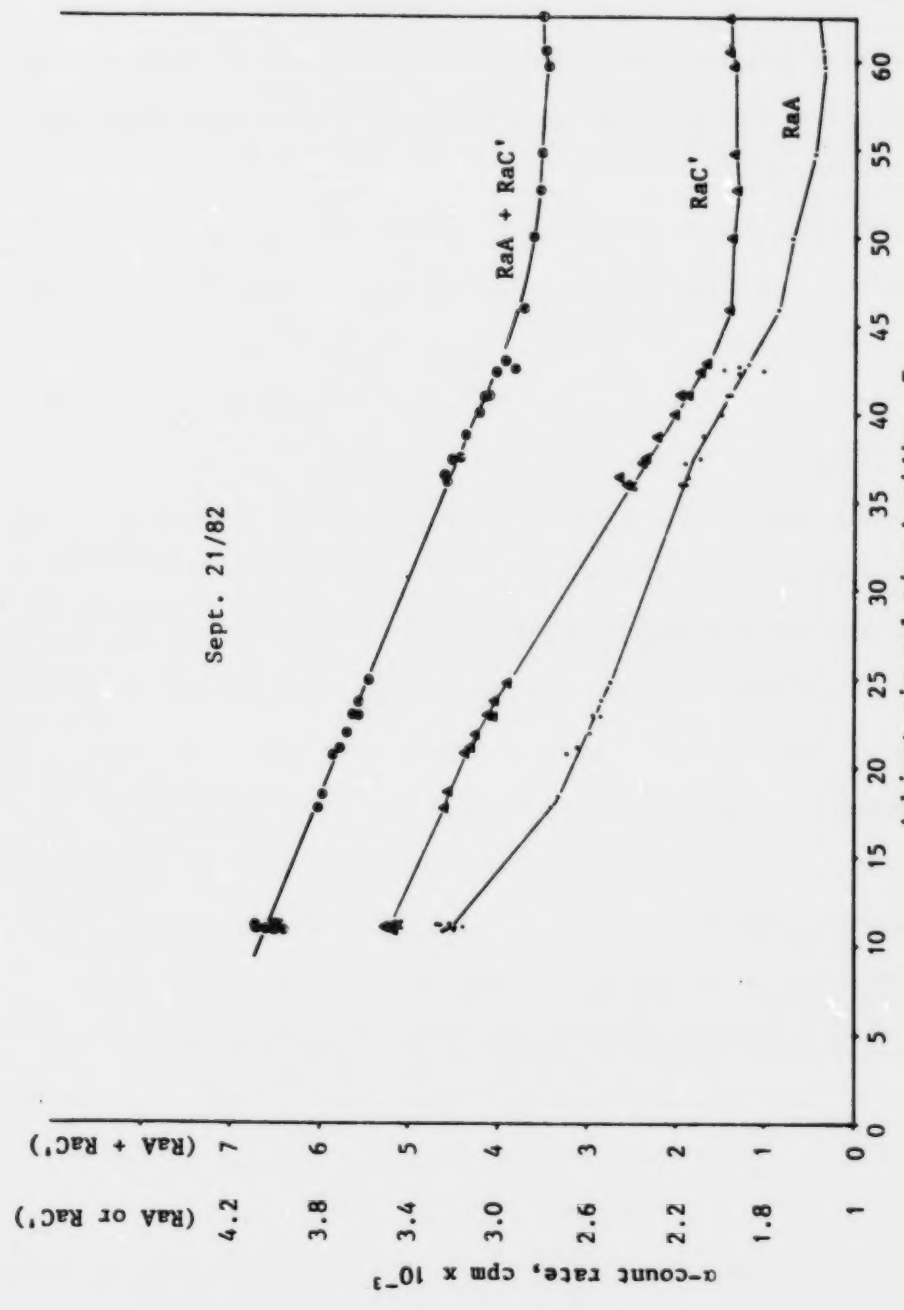

Fig. 1 - Alpha-count rate, cpm, as determined by the electrostatic collector (RaA, RaC' and RaA + RaC') versus the relative humidity of the air/radon mixture.

Several measurements for each value of RH were taken and an average value was calculated. The RH was varied from about 5% to 90%. (The same type of experiments were also carried out in the radon/thoron room, but the results are somewhat more complex because of the role of aerosol type, concentration and size distribution, and some unknown trace gases. Experiments were also conducted with thoron gas.).

Figure 1 shows an inverse linear relationship between total α-count, upper curve, and RH from about 10% to 45% after which a 'saturation' effect is observed and the total α-count remains constant and independent of RH. These results are in very good agreement with those by Porstendörfer et al. (15), but they disagree with data by Watnick et al. (10,11), who found a linear relationship between 0 and 90% relative humidity. This effect is under further investigation.

The response of the instrument to sudden, e.g., step, changes in the thoron radiation level is illustrated in Fig. 2 and 3 where WL(Tn) is plotted versus time when the instrument is rapidly moved from a region of low WL(Tn) to the radon/thoron test facility (Fig. 2), and vice versa (Fig. 3). Notice that in the second example, i.e., Fig. 3, a radon/thoron mixture was present in the test facility. The WL(Tn) in the radon/thoron room was maintained within ± 15% over a period of 24 h. Although the response of the instrument depends on the ratio [ThC]/[ThB] (2,5), Fig. 2 and 3 show that a long time (>20 h) is required for the instrument to reach a steady-state condition and give the true reading. After this period of time, the instrument will follow changes in WL(Tn) with the corresponding time lag. This behaviour is not specific of the RGA-400, but characteristic of instruments operating on time-integrating principles. For radon, a similar behaviour is observed only that the time lag and period of time required to attain steady-state conditions

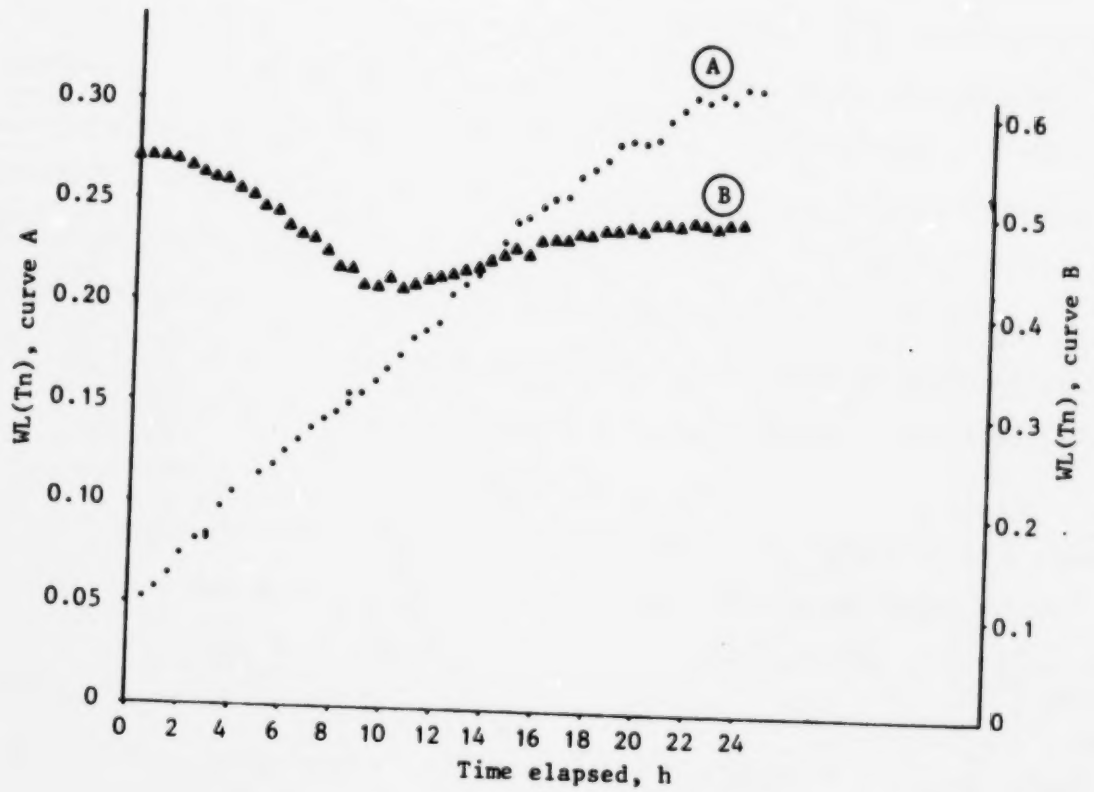

Fig. 2 - Response of the instrument to a sudden (step) increase in WL(Tn), curve A. The instrument was transferred from a region of low WL(Tn) to a high WL(Tn) area. The WL(Tn) in the latter versus time is shown in curve B.

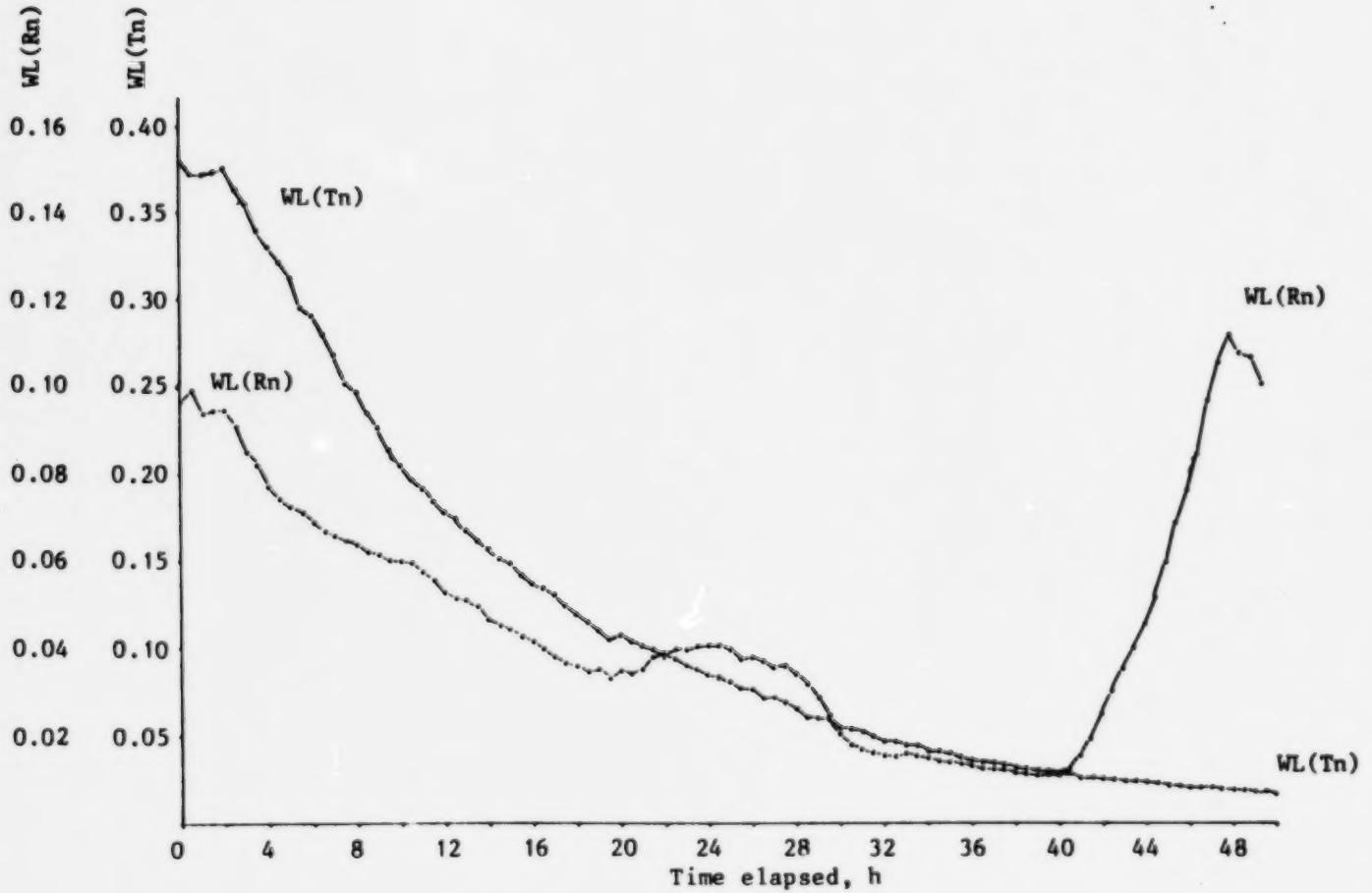

Fig. 3 - Response of the instrument to a sudden (step) decrease in WL(Tn). The instrument was transferred from a region of high WL(Tn) to a very low WL(Tn) area. The experiment was carried out in a radon/thoron atmosphere. WL(Rn) is also shown.

are correspondingly shorter because of the shorter half-lives of RaA and RaC' (5). The case of thoron has been illustrated here because it is the worst case that can be encountered. In general, natural environments have substantially higher radon levels than thoron levels. However, in some underground uranium mines the ratio WL(Tn)/WL(Rn) can attain values significantly greater than unity (1). Notice that in Fig. 3, WL(Rn) changes quite substantially with time instead of following the expected simple decay behaviour. This is so because of the presence of radon, but no thoron, in the room to where the instrument was transferred from the radon/thoron room. The radon originates from decay of Ra-226 in the subsoil, and finds its way through the floor by diffusion and convective transport mechanisms. The changes in WL(Rn) correlate quite well with the inverse of barometric pressure variations. The latter do not significantly affect surface thoron flux.

Figure 4 shows a typical WL trace of the monitor (RGA-400) in a radon/thoron atmosphere where the concentration of radon and thoron (curve C), and hence WL(Rn), curve B, and WL(Tn), curve A, vary independently. Also shown in the graph are some data obtained with a β-probe (pancake type) continuous monitoring system designed at our laboratory partly based on a similar system by Droullard and Holub (17). Notice that, as expected, an increase in thoron concentration is followed by a corresponding increase in WL(Tn), and vice versa. Also notice that, as indicated above, the instrument responds more readily to changes in WL(Rn) than to changes in WL(Tn).

Figures 5 and 6 show, respectively, typical print-out spectra from the instrument corresponding to the electrostatic collector and sampling head filter. Identified in the spectra are the different daughter products of radon and thoron found in the radon/thoron room atmosphere.

WL(Rn) and WL(Tn) data from the instrument were compared with grab-

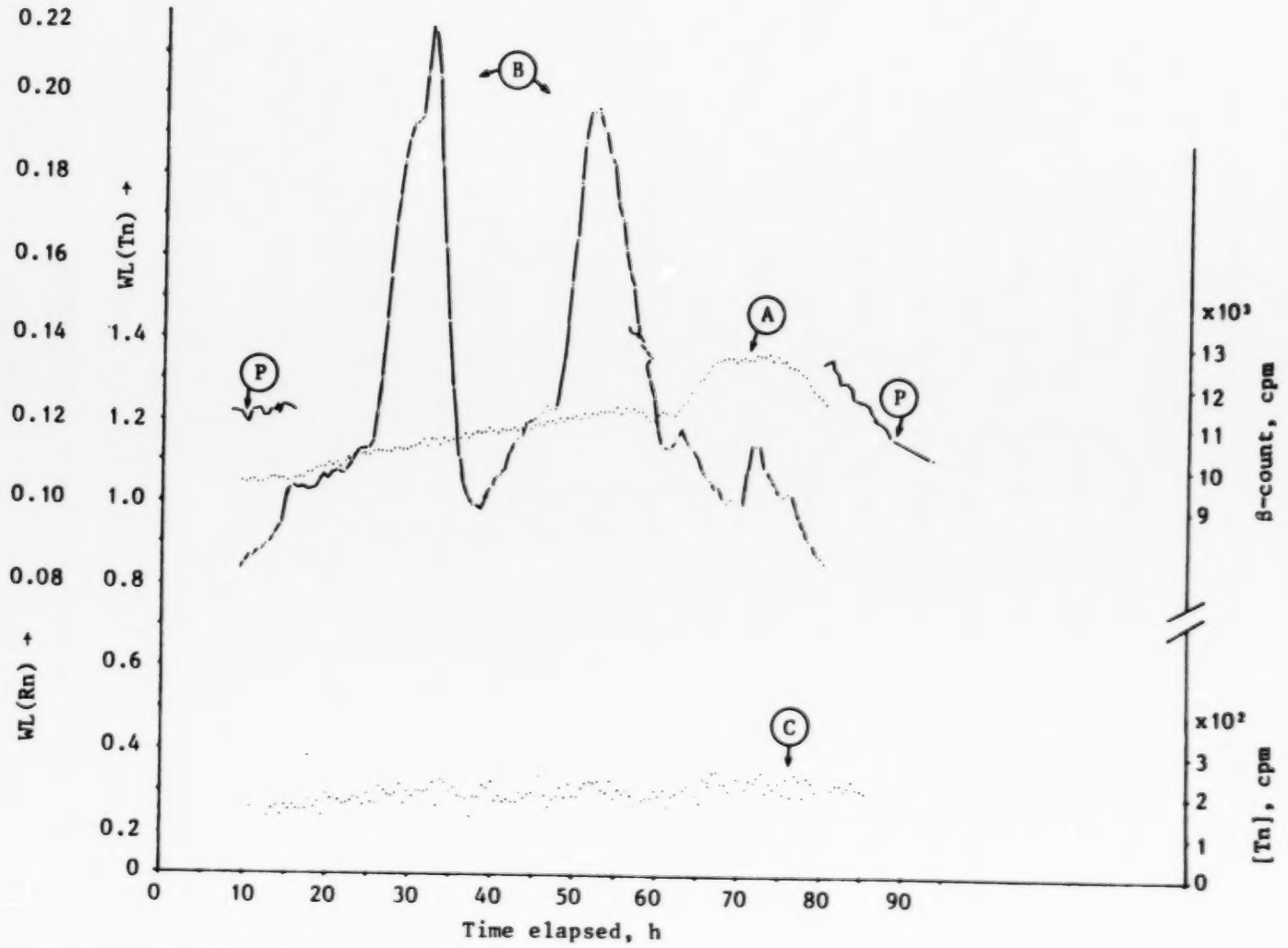

Fig. 4 - WL(Rn), curve B, WL(Tn), curve A, β-count, curve P, and thoron gas concentration, [Tn], in cpm (1 cpm ∿ 2 pCi/L), curve C, versus time.

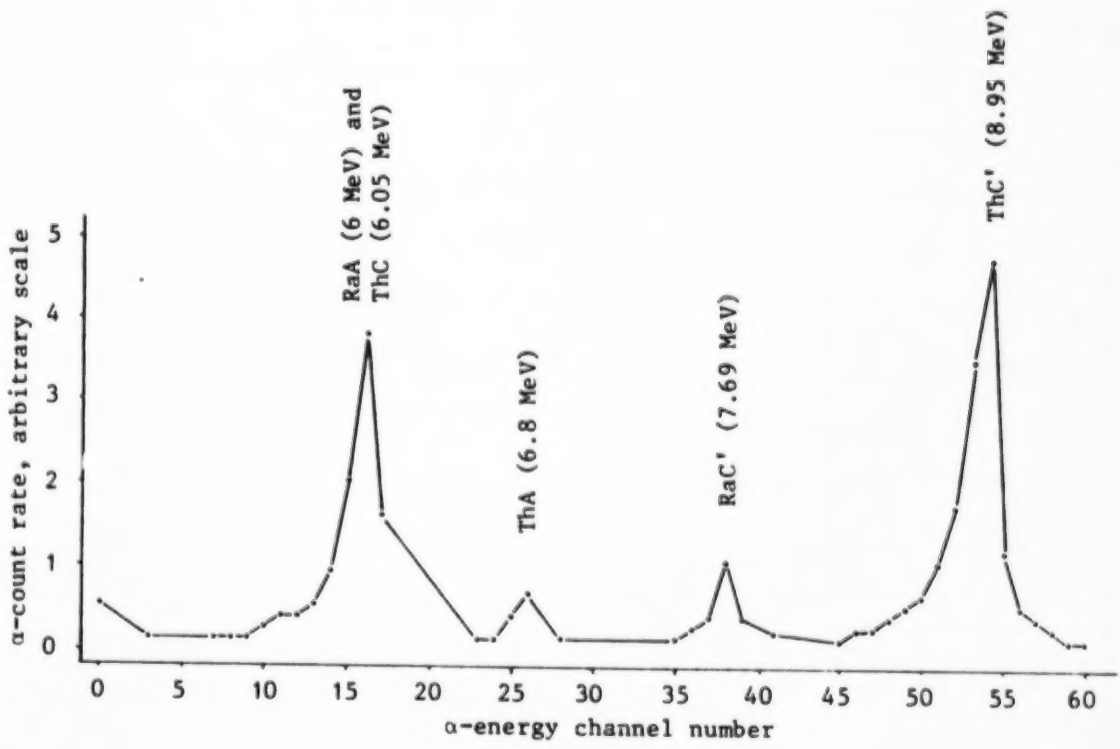

Fig. 5 - Alpha-spectrum from electrostatic collector for a typical run of the instrument in a radon/thoron mixture atmosphere.

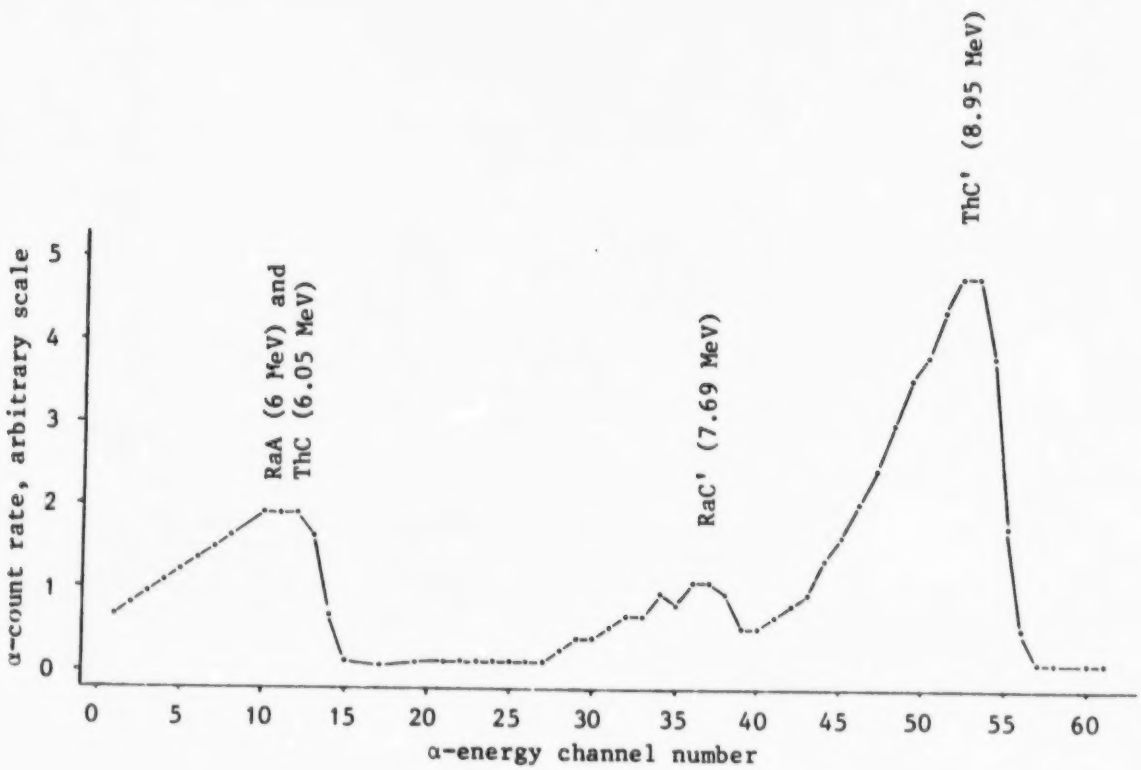

Fig. 6 - Alpha-spectrum from filter facing primary detector for a typical run of the instrument in a radon/thoron mixture atmosphere. Spectrum is broadened and its low energy end shifted toward lower energies as compared with the electrostatic collector because of α-energy absorption in the filter.

sampling data. Measurements in the radon/thoron test facility were carried out with radon/radon daughter atmospheres, thoron/thoron daughter atmospheres, and with a mixture of both. The Thomas-Tsivoglou, Kusnetz and Markov methods were used for radon daughters (18,19,20). A gross α-count method (21,22) and two gross α-count method (22) were used for thoron daughters. For radon/thoron mixtures a 5 α-count method developed by Khan et al. (23) was employed. Measurements were carried out mainly at low aerosol concentrations $\sim 1.0 \times 10^3$ cm^{-3}, a most unfavourable situation, to test the instrument sampling head for plate-out. Other measurements were conducted at much higher aerosol concentrations ($>2 \times 10^5$ cm^{-3}). The results are as follows:

1. A systematic underestimation of about 30% was observed for WL(Rn) and WL(Tn), as measured by the instrument, when compared with grab-sampling methods. Measurements were conducted, respectively, in radon/radon daughter atmospheres only and thoron/thoron daughter atmospheres only in the radon/thoron test facility;
2. A similar effect to that indicated in item 1 was observed when the instrument was in radon/thoron mixtures. The analysis in this case is, however, somewhat more complex because of photopeak overlap, which is further complicated by the long half-life of ThB (10.6 hr) which determines the decay of ThC and ThC'. The same applies to the analysis of WL(Tn) in item 1.

In all cases, above, the disagreement between the instrument reading and grab-sampling is partly due to incorrect conversion factors (see Equations 1 and 2) initially implemented in the instrument software package, based on preliminary experimental data. (Note: it is a relatively straight forward matter to change these conversion factors in the software package). For the case of radon/thoron mixtures, photopeak overlap (RaA and ThC) is a difficult

problem as both radioisotopes have the same α-energy (about 50 keV separation). Hence, there is an intrinsic difficulty in determining RaA and ThC separately by continuous counting using time-integrating methods. At present, modifications in the instrument are being introduced for better energy resolution, but most importantly, software changes will soon be implemented with more realistic analytical procedures to better deal with this problem.

REMARKS AND CONCLUSIONS

It should be indicated in passing that plate-out of daughter products in sampling heads is an important problem in any radiation instrument, particularly at low aerosol concentrations. This problem has not been dealt with here, but it is treated in detail elsewhere (2,3). Furthermore, all sampling methods used are affected by a certain error, quite substantial in many cases, which depends on the method itself and the radiation level to be measured. This is particularly important for methods designed to determine radon/thoron mixtures (23). Hence, some disagreement arises from the grab-sampling method used itself.

Improvements will be introduced in the instrument based on past and present extensive experimentation. Particularly, some software modifications should be implemented in the near future to minimize or eliminate some of the present limitations or deficiencies.

The RGA-400 is quite a flexible, versatile and powerful instrument which should prove quite useful in environmental monitoring for health physics, occupational and engineering purposes. The memory and α-spectroscopy capabilities of the instrument are particularly noteworthy and its flexibility ideally suitable for theoretical applications in addition to the above experimental uses.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of A. Frattini in conducting some experimental work and in preparing the illustrations in this paper. The RGA-400 has been supported under contract DSS-23SQ23440-9-9017 (J. Bigu, Scientific Authority) by CANMET (Energy, Mines and Resources Canada) as part of a long-term program aimed at stimulating the development of advanced instrumentation for better environmental and personal monitoring.

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APPENDIX

The factor Z_s in Equation 5 is given by:

$$Z_s = \Sigma_i Z_i \qquad \text{Eq A-1}$$

where, Z_i refers to the Z factor for the i-th α-radioisotope.

It can be shown (9,24) that:

$$Z_s(A) = (T_2 - T_1) + \tau_A(e^{-\lambda_A T_2} - e^{-\lambda_A T_1}) \qquad \text{Eq A-2}$$

where, $\tau_A = 1/\lambda_A$, and where the symbol A refers to RaA or ThA, and

$$Z_s(C) = (T_2 - T_1) + M(e^{-\lambda_A T_2} - e^{-\lambda_A T_1}) + N(e^{-\lambda_B T_2} - e^{-\lambda_B T_1}) - P(e^{-\lambda_C T_2} - e^{-\lambda_C T_1}) \qquad \text{Eq A-3}$$

where the symbols B and C refer, respectively, to RaB or ThB and RaC' or ThC. The symbols M, N and P are functions of the radioactive decay constants of the radioisotopes plate-out in the electrostatic collector (24).